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SURFACE WIND FORECASTING USING GENERALIZED OPERATOR MODEL OUTPUT STATISTICS

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1. INTRODUCTION

This paper addresses the problem of forecasting wind speed and direction at the surface for any random location. The procedure used is an extension of the regionalized Model Output Statistics (MOS) equations concept used at TDL for most of its MOS products. The extension is termed as a generalized operator (G.O.) in the context that the entire conterminous United States (CONUS) is considered as one region. As such, the use of such an equation will be valid at any location within the CONUS--an essential and vital condition. This paper presents an experiment comparing the ability of a simple G.O. MOS equation's ability to forecast surface winds with a set of single station (S.S.) MOS equations used as the control or competitor. An enhancement of the G.O. through local unbiasing is also considered with encouraging results.

2. THE GENERALIZED OPERATOR MOS MODEL

The idea of a generalized operator equation is not new. Harris, et al. (1963, 1965) successfully demonstrated this concept as a diagnostic tool. They detailed a basic philosophy behind a statistical generalized operator and proceeded to illustrate their point by developing equations that would estimate ceiling, visibility, and total cloud amount as viewed by a surface observer given only basic upper air information. NWS/TDL has for many years used the G.O. approach for many MOS products by using a regional collection of station data to stabilize their forecast equations. Although not purely a "general" approach, these regional equations that were derived from civilian airports' meteorological data can be applied to other locations within the same region. The Air Weather Service (AWS) employs this capability to make twice-daily operational MOS forecasts of ceiling, visibility, cloud amount, probability of precipitation, etc., for U.S. Air Force and Army locations within the CONUS. Two MOS forecast elements not available for this special support, however, are surface temperature and wind. These two products are available only from single station equations and valid only at select civilian locations. Since the AWS needs these elements, a potential solution is to use the G.O. approach. Therefore, a G.O. MOS model for forecasting surface wind is specifically addressed in this paper and experiment.

Equations are developed from all available data within the realm of solution (e.g., the entire CONUS), pooled together as one large database. The data includes surface observations, LFM numerical model outputs, and location specific constants such as latitude, longitude, elevation, etc. From this one database the standard multiple linear stepwise regression solution provides the coefficients necessary to forecast wind speed (S), east-west wind component (u), and north-south wind component (v)--direction is computed by trigonometry from the u and v component forecasts. The data are unaltered; that is, means are not removed, standardized, normalized, or otherwise modified. TDL has a hardwired limitation in the screening regression software which limits the maximum screened predictor set to 20. In deriving the G.O. equations this limit is often reached. Since the single station Mos equations normally stop selection at around 10 to 12 predictors, this 20 predictor limitation is not considered too binding on the G.O. model. At least the G.O. model has an opportunity to pick several predictors that may be important to only a few stations throughout the country beyond the basic common ones such as the 850-mb and boundary layer wind.

Harris et al. (1963, 1965) found that the preferred choices in predictors were those with means removed (called anomoly variables) with a few raw predictors being picked up. No standardized predictors were selected. Since the TDL MOS system does not have the operational facility to remove means before entering regression, this experiment focuses first on the ability of only raw predictors to hold up in a G.O. approach and secondly to examine if a post removal of lack of fit from the forecasts could improve local verifications.

Therefore, the G.O. model in this experiment will have two configurations: unaltered and local unbiasing. The unaltered version refers simply to the G.O. model being applied at all locations without consideration of local effects. The local unbiasing version refers to an attempt to improve on the G.O. model's forecasts by considering the bias at each separate location. Using a local bias as a correction will be referred to as the equivalent single station (E.S.S.) model. The corrections used by the E.S.S. model are determined by solving the G.O. at each forecast location over the dependent sample and computing the difference between the local forecast and local observed means for S, u, and v. These corrections are then used to adjust the G.O. model's output simply by subtraction. For example, if the G.O. model makes a forecast S' and the local bias is $b=\overline{S'}-\overline{S}$, then the E.S.S. forecast would be $S''=S'-b$.

3. EXPERIMENTAL DESIGN

Before the operational acceptance of a G.O. MOS equation set for surface wind forecasting is made, it must be established that this procedure makes useful and sufficiently accurate forecasts. Sufficiency can be in the eye of the beholder, of course, but here it will be defined more objectively in terms of error analysis. Specifically, the G.O. model will be judged adequate if its errors are no worse than one reportable value from forecasts made by the control model--the single station MOS equations. These limits are 1 kt and 10^0 for wind speed and direction, respectively

Twenty test sites were selected for the independent verification.

No.	Call Letters	Name	No.	Call Letters	Name
12842	TPA	Tampa, Fla.	23050	ABQ	Albuquerque, N. Mex.
12916	MSY	New Orleans, La.	23065	GLD	Goodland, Kans.
12921	SAT	San Antonio, Tex.	23154	ELY	Ely, Nev.
13874	ATL	Atlanta, Ga.	23188	SAN	San Diego, Calif.
13994	STL	St. Louis, Mo.	24021	LND	Lander, Wyo.
14733	BUF	Buffalo, N.Y.	24157	GEG	Spokane, Wash.
14740	BDL	Hartford, Conn.	24229	PDX	Portland, Oreg.
14742	BTV	Burlington, Vt.	93139	FAT	Fresno, Calif.
14898	GRB	Green Bay, Wis.	93721	BAL	Baltimore, Md.
14943	SUX	Sioux City, Iowa	94847	DTW	Detroit, Mich.

Data samples were identified from 0000 GMT cycle LFM forecast fields, local observation files, and selected location specific constants:

(1) Dependent sample: April-September seasons for 1973-75 (3 years).

(2) Independent sample: April-September seasons for 1976-77 (2 years).

Single station MOS equations valid at 18 hours were developed over the dependent sample for each of the 20 test sites. These equations are the control.

Generalized operator MOS equations valid at 18 hours were developed from a large sample of available CONUS surface reporting stations <u>excluding</u> the 20 test sites. The G.O. MOS equation set used 213 other stations over the dependent sample.

Verification statistics for wind speed are valid for all nonmissing verifying observations, but wind direction samples were deleted if either forecast or observed wind speed was less than 2 kts. Comparisons were made at each of the 20 test sites plus overall scores. Key measures were the differences in statistics and the percent improvement. The two variables examined were wind speed and wind direction--the u and v components were not verified explicitly. Wind speeds were inflated before verification.[1] All conclusions were based on the independent verification sample of dates and locations given above.

4. EXPERIMENTAL RESULTS

Verification for each station is displayed on a series of figures (1 through 4). These figures illustrate not only how the G.O., E.S.S., and S.S. models performed at each test site, but also how they performed and compared spatially across the country. This suggests that some variations are due to location parameterizations for which the G.O. model may not be accounting.

Fig. 1 compares the mean absolute error (MAE)[2] differences between the S.S. and G.O. models for wind speed forecasts. Notice that in no case was the difference between the models greater than 1 kt. The line separating S.S. vs. G.O. model advantages is scalloped for ease of subjective interpretation but should not be completely believed to reflect such easily collectable areas of advantage. In other words, it appears that the S.S. model is superior along the Atlantic through Gulf coastal states, but there is no strict guarantee of this--just a hint.

Fig. 2 is similar to Fig. 1, but compares the S.S. and E.S.S. verifications. One station had a difference exceeding the 1 kt criterion (1.67 at Fresno, Calif.).

Figs. 3 and 4 provide spatial comparisons between the S.S. vs. G.O. and S.S. vs. E.S.S., respectively, for wind direction MAE's. A significant analysis here is the number of stations which favored the S.S. model by 10^0 or more.

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[1] Inflated wind $\hat{S}'$ uses mean wind speed ($\bar{S}$) and the forecast equations correlation coefficient (R) thus: $\hat{S}' = \bar{S}+(\hat{S}-\bar{S})/R$, where $\bar{S}$ and R are local statistics for the single station equations, but the global values for the G.O. equation.

[2] MAE is defined as $\frac{1}{N} \sum_{i=1}^{N} |Fcst(i)-Obsv(i)|$

Fig. 3 shows 15 locations to have better forecasts from the S.S. model with 9 of these being better by more than 10^0. It is also significant to note that by using bias adjustments on the G.O. model (i.e., the E.S.S. model), 15 locations still are better with the S.S. model, but now only 3 exceed the 10^0 criterion.

Table 1 compares MAE and root mean square error (RMSE)[3] among the three forecast models. The G.O. produces a degradation to the forecasts on the average of only 0.2 kt MAE or 5.5% over the S.S. model. The E.S.S. model does not improve the MAE score, being on the average 0.3 kt or 10% degraded. RMSE percentages reflect the same relative conclusion. TDL's wind speed MOS forecasts are also judged on their ability to verify in fixed ranges, or categories, of speeds. As depicted in Table 2 the E.S.S. model gains a noticeable advantage over the G.O. model in terms of percent correct forecasts and Heidke skill score. Given that the possible range of improvement is defined by the difference of scores between the S.S. and the G.O. models, the E.S.S. accounts for 56% (.018/.032) of the potential improvement in percent correct and 85% (.039/.046) in skill score.

Table 3 compares the three MOS models for wind direction verification in terms of MAE and RMSE. Category verification is not made for wind direction. These statistics support the comments made about Figs. 3 and 4; that is, the E.S.S. model improves the G.O. model considerably and becomes very competitive and useful. The MAE, for example, is 45.0^0 for E.S.S. and 42.8^0 for S.S., a mere difference of 2.2^0 (much less than the 10^0 criterion). The E.S.S. is only 5% below the S.S. model's verification, but more importantly is nearly 9% better than the G.O. model.

5. REMARKS AND CONCLUSIONS

A. Generalized Operator Equation

Table 4 gives the G.O. equation. Notice that 75% of the 20 predictors are wind related terms, and at least one is a location constant (station longitude).

B. Special Notes

There are several interesting results and asides which deserve particular attention. First, in terms of wind speed forecasting, both the G.O. and the E.S.S. models did sufficiently well in comparison to the control S.S. model.

As a special set of variations on the theme, I tried to improve the E.S.S. by using local observed means and an estimated local correlation coefficient for the inflation procedure. The result of these attempts is that the global values of $\overline{S}$ and R are the correct values to use.

Figure 5 shows the CONUS-wide biases between the G.O. equation for wind speed and the local observed mean wind speed. Examination suggests that such a bias field is analyzable and interpretable, particularly in the smoother terrain areas of the country. This is an important feature for the E.S.S. model if it is to be applied to locations not originally in the development sample or for those locations that have no history upon which to base a climatology.

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3 $$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\mathrm{Fcst}(i)-\mathrm{Obsv}(i))^2}$$

Second, for forecasting wind direction, the G.O. model did not perform as well as hoped (cite Fig. 3). The E.S.S. model came to the rescue, so to speak, being only 2^0 off the MAE of the S.S. model's verification. The need to adjust the u and v components before computing wind direction (a trigonometric solution) is borne out as a desirable feature.

C. Corroboration and Potential Improvements

There are also some very important details to point out with regard to constructing a G.O. model.

(1) Harris, et al. (1963, 1965) describe the predictand data to be standardized and normalized before entering regression against predictors which are either in their raw or anomolous form. Apparently, the variations of the elements about their local means have more predictive qualities than their raw measures. This G.O. MOS wind experiment did not have this feature available and, therefore, was not included. Pure, unadjusted values were used in regression. It was only with the E.S.S. model that any attempt was made to allow for local biases.

(2) The experiment in this paper attacked the problem of forecasting surface winds--a very locally influenced meteorological element. Lee (1975) regards surface winds to depend to a large degree on atmospheric stability and surface, or terrain, roughness. This experiment did not have any surface roughness constants available, nor did it consider any stability indices as potential predictors. This speaks of possible sources of improvement to already acceptable results. Anthes and Warner (1974) also deemed variations in topography as important forcing functions that modify mesoscale wind flow. Harris and MacMonegle (1965) in forecasting total cloud amount introduced local orographic and coastal effect terms into their generalized operator model, of which some were selected as predictors.

(3) Lange (1973) did some particularly pertinent work in the forecasting of surface winds. He used prediction errors from the previous dynamic model forecasts as feedback predictors. He also used orographic effects in the wind forecast models and found that short-range forecasts using purely statistical predictors such as persistence were useful. However, dynamic predictors become necessary for longer period forecasts. More importantly, Lange found that straight, unaltered computer produced forecasts from his regional equations were better than coastal single station forecasts in both wind direction and speed and competitive with the better results of the inland single station models. Since Lange had more apparent success than this experiment in "beating" the S.S. model, it is again encouraging that the lack of certain predictors such as orographic effects and error feedback is part of the G.O. model's shortfall. The objective of this experiment, mind you, was not to beat the S.S. model, but to attain an acceptable closeness that would make a simple G.O. or E.S.S. model have some operational utility. If it turned out to be superior, so much the better.

D. Operational Value

What then are some of the benefits of a G.O./E.S.S. MOS system? First, development of new equations could be greatly simplified and accelerated with fewer equations to solve and check. Second, the G.O./E.S.S. models would allow for the support of many more points than available to the S.S. solution. This is particularly important to current MOS support to the AWS and to future FAA support. Third, considerable mass storage savings could be gained over S.S. models. Typical savings for this one product alone, for example, is in the area of a 95% reduction (about 5 cylinders for IBM 360/195 disc space down to 5 tracks). Fourth, potential applications could escape the confines of a large computer complex. A regional computer system using smaller units could generate MOS wind forecasts upon demand if selected LFM values were made available. This can be particularly appealing to military applications in making point forecasts in a tactical, mobile environment where reliance on centralized production support can often be interrupted.

6. ACKNOWLEDGEMENTS

I want to express my deepest gratitude to Captain Charles French for bearing the brunt of work involved in cranking out all the trial G.O. and E.S.S. equation sets. Mr. Gary Carter deserves many thanks for helping design this test, picking the 20 test sites, and furnishing the control single station equations. Dr. Robert G. Miller provided the basic hope and direction to the G.O./E.S.S. concepts and appropriate understanding when problems arose. Thanks to Marge Brown of the Systems Development Office who typed this paper.

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Table 1. Wind speed forecast comparisons. Mean absolute error (MAE) and root mean square error (RMSE) are given in knots for the three sets of forecasts: single station (S.S.), generalized operator (G.O.), and equivalent single station (E.S.S.).

STATION		MAE			RMSE		
		S.S.	G.O.	E.S.S.	S.S.	G.O.	E.S.S.
TPA	12842	2.12	2.87	2.40	2.74	3.56	3.15
MSY	12916	1.99	2.42	2.41	2.61	3.13	3.12
SAT	12921	2.43	2.62	2.50	3.07	3.34	3.23
ATL	13874	2.43	2.47	2.60	3.18	3.11	3.27
STL	13994	2.66	2.63	3.07	3.37	3.46	3.81
BUF	14733	3.07	3.17	3.15	3.97	4.04	4.00
BDL	14740	2.85	3.17	3.11	3.61	4.04	3.97
BTV	14742	2.83	3.35	3.12	3.59	4.31	4.05
GRB	14898	3.00	2.84	2.85	3.83	3.70	2.71
SUX	14943	2.99	2.91	3.13	3.81	3.75	3.98
ABQ	23050	3.34	3.32	3.30	4.82	4.99	5.02
CLD	23065	3.76	4.03	4.24	4.76	5.09	5.38
ELY	23154	4.31	4.17	4.03	5.41	5.51	5.24
SAN	23188	2.45	3.24	3.19	3.26	4.01	3.97
LND	24021	3.52	3.09	4.09	4.51	4.07	5.31
GEG	24157	2.93	2.94	2.64	3.63	3.79	3.46
PDX	24229	2.78	2.77	3.21	3.69	3.60	3.97
FAT	93193	1.98	2.41	3.65	2.63	3.30	4.39
BAL	93721	2.50	2.64	2.62	3.20	3.36	3.34
DTW	94847	3.08	3.00	3.25	3.92	3.84	4.18
Overall		2.84	3.00	3.13	3.74	3.95	4.08

Table 2. Percent correct and Heidke skill score of wind speed computed from 5 category contingency tables. The 5 categories are <8, to <13, 13 to <18, 18 to <23, >23 kt.

STATION		Percent Corr.			Heidke Skill		
		S.S.	G.O.	E.S.S.	S.S.	G.O.	E.S.S.
TPA	12842	54.6	51.7	51.1	.202	.162	.179
MSY	12916	64.0	63.4	62.6	.327	.310	.297
SAT	12921	53.1	49.7	49.7	.223	.215	.217
ATL	13874	60.0	60.6	60.6	.276	.286	.264
STL	13994	59.7	55.4	54.0	.368	.324	.289
BUF	14733	48.0	47.1	45.7	.272	.248	.231
BDL	14740	50.0	47.1	47.1	.231	.215	.215
BTV	14742	54.6	46.0	48.3	.274	.193	.208
GRB	14898	49.1	52.0	50.3	.259	.300	.276
SUX	14943	47.7	49.7	45.1	.250	.279	.221
ABQ	23050	54.3	49.7	51.4	.207	.168	.169
CLD	23065	40.9	38.9	35.7	.196	.154	.121
ELY	23154	48.9	44.6	41.7	.233	.155	.141
SAN	23188	50.6	42.3	43.1	.092	-.021	-.007
LND	24021	70.3	53.7	76.9	.188	.164	.102
GEG	24157	51.1	52.0	56.3	.208	.226	.301
PDX	24229	62.0	54.9	66.6	.152	.100	.093
FAT	93193	69.4	62.6	73.4	.104	.138	.155
BAL	93721	53.1	51.1	51.4	.252	.231	.238
DTW	94847	45.1	48.9	46.6	.203	.260	.242
Overall		54.3	51.1	52.9	.293	.247	.286

Table 3. Mean absolute error (MAE) and root mean square error (RMSE) in degrees for the three sets of forecasts. Sample was depleted for any case where the forecast or observed wind speed was < 2 kt.

STATION		MAE			RMSE		
		S.S.	G.O.	E.S.S.	S.S.	G.O.	E.S.S.
TPA	12842	43.2	61.2	43.3	61.1	79.7	59.2
MSY	12916	44.0	55.3	47.3	60.1	72.6	64.4
SAT	12921	33.3	32.2	32.8	47.5	45.5	46.1
ATL	13874	44.1	41.6	39.9	60.3	55.9	54.7
STL	13994	35.0	35.6	35.8	49.7	49.6	49.7
BUF	14733	31.8	33.3	34.6	47.2	46.7	48.8
BDL	14740	40.1	40.1	39.6	55.7	56.2	55.1
BTV	14742	38.4	48.6	48.2	54.3	67.4	63.3
GRB	14898	36.9	37.3	37.2	53.9	54.0	53.9
SUX	14943	27.7	28.8	28.8	42.2	43.6	43.7
ABQ	23050	57.6	68.5	59.9	74.2	84.6	77.2
CLD	23065	40.0	43.6	43.9	58.2	61.4	60.9
ELY	23154	54.0	53.6	55.0	72.4	71.0	72.2
SAN	23188	38.6	50.6	43.3	47.9	64.7	53.6
LND	24021	73.2	99.0	84.4	88.3	113.2	98.7
GEG	24157	39.2	58.0	49.2	56.9	74.1	65.3
PDX	24229	56.6	71.1	66.8	74.7	88.3	84.7
FAT	93193	57.9	68.6	60.7	75.2	86.9	77.3
BAL	93721	38.1	36.8	36.8	53.0	53.3	53.3
DTW	94847	32.2	31.1	33.0	48.2	45.9	47.8
Overall		42.8	49.3	45.0	59.9	67.4	61.8

Table 4. G.O. MOS equation to forecast CONUS surface winds at any location. Predictors 1 through 19 are all scaler terms taken from NMC's LFM. Predictors are in the same order as the screening regression solution selected. Abbreviations used are East-West wind component (U), North-South wind component (V), boundary layer (BL), and relative humidity (RH). The predictors were either unsmoothed or passed through a five-point smoother as noted by the numbers in parentheses.

Pred No.	Projection Hour	Predictor Description	Coefficients U-component	V-component	Speed
0	0	Constant	-5.9429	2.3240	17.106
1	18	BL V (5)	-.048099	.33950	-.0034239
2	24	850-mb V (5)	-.17071	.23297	.26736
3	24	BL U (5)	.26536	-.0051883	-.066219
4	24	700-mb V (0)	.0090272	-.0070011	-.16238
5	24	BL V (5)	.058289	.22539	-.091470
6	18	850-mb Geostrophic V (0)	-.0013232	.028699	-.065631
7	24	850-mb Geostrophic U (5)	.095835	.045361	-.31053
8	18	BL U (5)	.32716	.21299	.022174
9	12	850-mb U (0)	.29993	-.041197	-.043591
10	12	850-mb Height (0)	.0015617	.0003457	-.0070164
11	12	850-mb Speed (0)	.023402	.033577	.13434
12	24	700-mb Speed (5)	.026652	-.059801	-.098154
13	24	500-mb Relative Vorticity (5)	.05696	.0064022	.096946
14	18	850-mb Geostrophic Speed (0)	.019944	-.014572	.066651
15	18	850-mb Speed (5)	.046210	-.065162	.22750
16	24	850-mb Speed (5)	-.016567	.031666	.33865
17	12	850-mb V (0)	-.023138	.25658	.10877
18	18	RH, Top of BL to 720 mb (5)	-.0089797	-.026422	-.014067
19	18	RH, BL 6-hour change (5)	-.0040505	-.0073639	.035008
20	0	Station Longitude (0)	.028722	-.0053546	-.0069806
SAMPLE SIZE = 90357		MEAN =	1.340	1.160	9.220
		CORRELATION COEFFICIENT =	.668	.705	.556

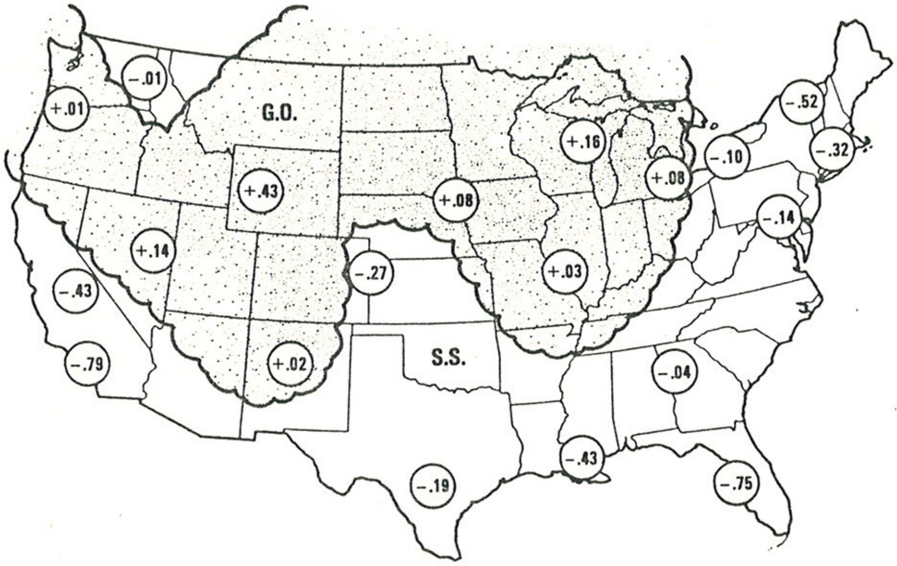

Figure 1. Speed comparisons of MAE between single station (S.S.) and generalized operator (G.O.) equations. Values are MAE of the S.S. minus MAE of the G.O. in units of knots.

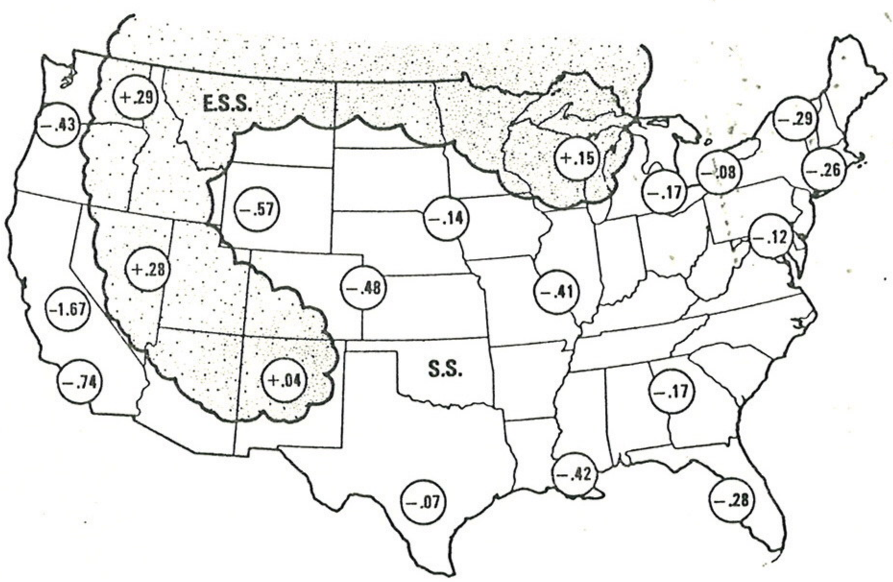

Figure 2. Speed comparisons of MAE between single station (S.S.) and equivalent single station (E.S.S.) equations. Values are MAE of the S.S. minus MAE of the E.S.S. in units of knots.

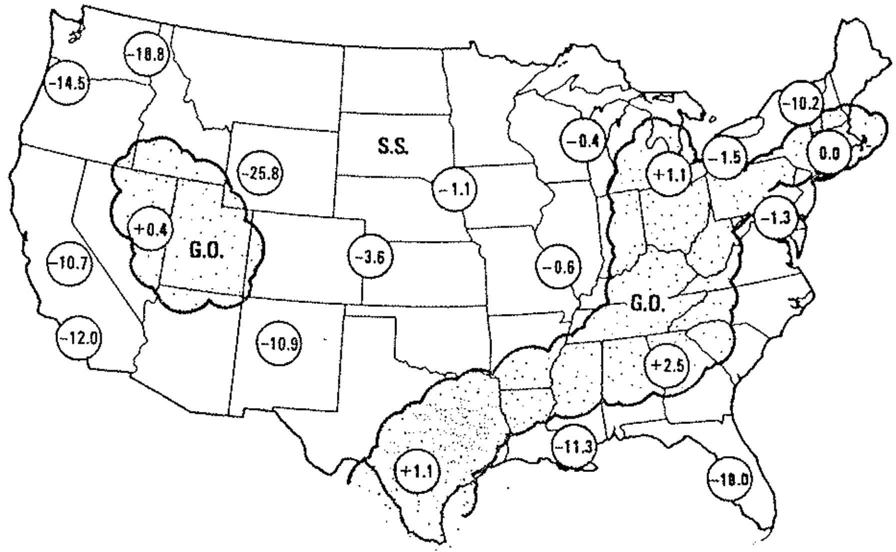

Figure 3. Direction comparisons of MAE between S.S. and G.O. equations. Values are MAE of the S.S. minus MAE of the G.O. in units of degrees of the compass.

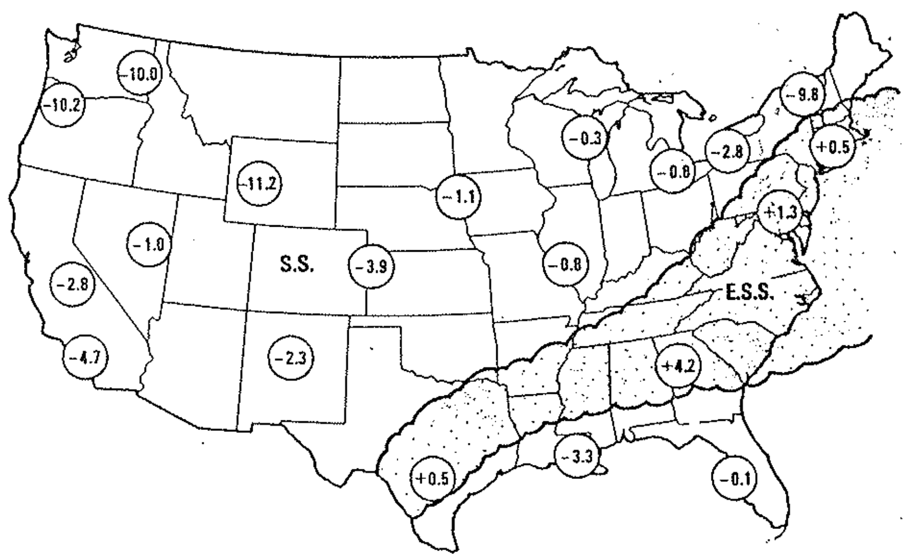

Figure 4. Direction comparisons of MAE between S.S. and E.S.S. equations. Values are MAE of the S.S. minus MAE of the E.S.S. in units of degrees of the compass.

Figure 5. Analysis of wind speed biases for the generalized operator MOS equation over the dependent sample. Units are knots. Bias is the mean forecast wind speed minus the mean observed wind speed. Bias is computed at each location separately and contoured. Shaded area is negative bias. Clear area is positive bias.